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History of Quaternary Science

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Introduction

The Quaternary sciences represent the systematic study of the Quaternary, or most recent geologic period. This period is generally characterized by a series of glaciations, or ice ages, interspersed with relatively warm, interglacial intervals, such as the current interglacial, the Holocene. The study of Quaternary environments began in the late eighteenth century. Quaternary geology and paleontology came of age in the nineteenth century, and other important aspects of Quaternary science, such as paleoceanography (*see* Paleoceanography), paleoecology, and paleoclimatology (*see* Introduction), developed to a much greater extent in the twentieth century. As with many branches of science, the pioneers in Quaternary studies had to work hard to overcome many widely held, erroneous ideas from previous generations of scholars.

At the beginning of the nineteenth century, science itself was rapidly changing. Up until that time, university professors and other scholars who performed scientific research were mostly generalists who dabbled in many different fields. They looked upon themselves as natural historians, studying the workings of the natural world, as their whimsy led them. The early nineteenth century saw the beginnings of specialization in science. As the level of scientific knowledge was rapidly increasing, it was no longer possible for individual scholars to keep abreast of all the new discoveries. People began to devote their time and energy to one or just a few lines of research. This new, focused style of scientific study brought great leaps forward for science as a whole, and for Quaternary science, in particular, as we shall see, below.

Establishing the Geologic Framework

The term 'Quaternary' was coined by an Italian mining engineer, Giovanni Arduino (1714–95). He distinguished four orders of strata comprising all of Earth's history: Primary, Secondary, Tertiary, and Quaternary (Schneer (1969), p.10). Arduino (**Fig. 1**) distinguished four separate stages or 'orders' which he recognized on the basis of very large strata arranged one above the other.

These four 'orders' were expressed regionally in Italy, as the Atesine Alps, the Alpine foothills, the sub-Alpine hills, and the Po River plain, respectively. The term 'Quaternary' apparently was not used again until the French geologist Desnoyers (1829) used it to differentiate Tertiary from Younger strata in the Paris basin. It was redefined by another Frenchman Reboul (1833) to include all strata containing extant flora and fauna.

The Quaternary period, as we now know it, is divided into two epochs: the Pleistocene and the Holocene (*see* Overview). The history of these terms

Figure 1 Giovanni Arduino (1714–95).

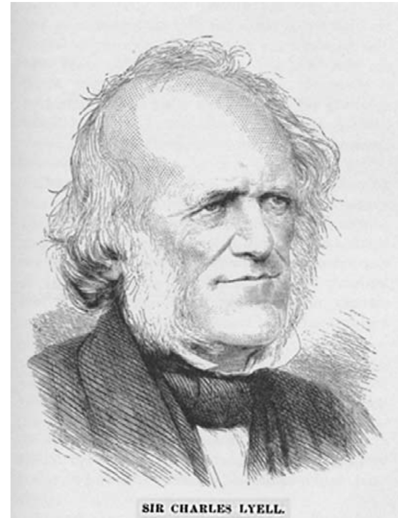

Figure 2 Charles Lyell (1797–1875).

is likewise complicated. The term 'Pleistocene' was coined by Scottish geologist, Charles Lyell (**Fig. 2**) in 1839, to replace his previous term 'Newer Pliocene' (1833).

Lyell defined the Pleistocene as the 'most recent' geologic era, and further specified that Pleistocene rocks and sediments are characterized by containing more than 90% fossil mollusks that are recognized as living species. As glacial theory began to take shape (see below), Forbes (1846) redefined the Pleistocene as equivalent to the 'Glacial Epoch.' Then Hörnes (1853) introduced the term Neogene to include Lyell's Miocene and Pliocene. In response, Lyell (1873) specified that the term Pleistocene should be used 'as strictly synonymous with post-Pliocene.' In the same publication, Lyell also separated the Pleistocene (glacial) from the 'Recent' (postglacial) time. The term 'Recent' was later replaced by the term 'Holocene' by Gervais (1867–69).

Thus, by the end of the nineteenth century, the stratigraphic nomenclature of the Quaternary period was firmly established (*see* Overview). However, no one knew when the Tertiary ended and the Quaternary began. In geology, it is standard procedure to designate a type locality that typifies such boundaries between major stratigraphic units. The 18th International Geological Congress (London, 1948) resolved to select a type locality for the Pliocene–Pleistocene (Tertiary–Quaternary) boundary. After three decades of deliberations, the Vrica section in Calabria, southern Italy, was finally selected. Hence the Plio-Pleistocene boundary was established at this site, where the boundary falls at ca. 1.64 Ma (Aguirre and Pasini, 1985; Bassett, 1985). Hilgen (1991) calibrated this age, based on an orbital forcing chronology, to an age of 1.81 Ma.

These age designations were only made possible through the invention of radiometric dating methods, which came about in the latter half of the twentieth century (see below).

The Discovery of Pleistocene Mammals

The threads of research that eventually led to modern Quaternary science came from a variety of disciplines, and were driven by scientific observations in a number of fields. One of these was the field of vertebrate paleontology (*see* Vertebrate Overview). As with many branches of science, pivotal discoveries often launch major new lines of research. One such discovery was made at a Pleistocene site in Kentucky, called Big Bone Lick. The site lies on a tributary of the Ohio River, about 30 km southwest of Cincinnati Ohio. It was the first major New World fossil locality known to Europeans. Baron Charles de Lougueuil, the commander of a French military expedition, may have been the first European to visit the site in 1739. He collected some mastodon fossils that were later studied by the French naturalists, Daubenton, Buffon, and Cuvier. Cuvier (1825) published a description of the Big Bone Lick mastodon remains. Inspired by this and other Pleistocene fossil discoveries, Cuvier developed his theory of global cooling that led to the extinction of these strange beasts.

In 1807, at the behest of Thomas Jefferson, William Clark conducted a major collecting expedition at Big Bone Lick that yielded about 300 specimens, most of which can still be found either at the National Museum of Natural History in Paris or at the Academy of Natural Sciences in Philadelphia. Thus, the fossils from this one site helped to launch Pleistocene vertebrate paleontology on two continents. The discovery of mastodon and other large Pleistocene mammal remains at this site sparked the imagination of scientists and politicians alike. In 1803, the United States purchased the Louisiana Territory from France. This territory included more than 2 million sq. km of land extending from the Mississippi River to the Rocky Mountains. When President Thomas Jefferson sent Meriwether Lewis and William Clark to explore and map this new American territory, he expected that they might find living specimens of mastodon and other large Pleistocene mammals, roaming the uncharted wilderness of the West. Jefferson was an avid naturalist, and took great interest in the fossil bones from Big Bone Lick.

Based on discoveries such as these, the field of vertebrate paleontology was starting to take shape during the late eighteenth and early nineteenth centuries. As discussed above, one of the most important leaders in this newly emerging field was the French scientist, Georges Cuvier (Fig. 3). At the start of the nineteenth century, Cuvier was a professor of animal anatomy at the Musée National d'Histoire Naturelle (National Museum of Natural History) in Paris.

Figure 3 Georges Cuvier (1769–1832).

An opponent of the theory of evolution, Cuvier's most important contribution to science was the establishment of extinction of ancient species, based on fossil records. Until the nineteenth century, most philosophers and natural historians rejected the idea that some species had died out, and that new species had evolved over time. Most Europeans held to a strict, literal interpretation of the Bible which dictated that the Earth was created in just 6 days, only a few thousand years ago. But the fossil record that was just beginning to be unearthed by a handful of paleontologists began to challenge this view.

Although Cuvier remained a Creationist, the fossils he was describing were re-shaping his views on the nature of that creation. Cuvier believed in the great antiquity of the Earth, and held that more-or-less modern conditions had been in existence for most of Earth's history. However, in order to explain the extinction of species Cuvier had seen in the fossil record, he invoked periodic 'revolutions' in Earth's history. Each 'revolution' was a natural event that had brought about the extinction of a number of species. Unlike others of his time (notably the Reverend William Buckland, who invoked the Biblical Flood), Cuvier did not equate these 'revolutions' with Biblical or historical events.

Cuvier considered that the last great 'revolution,' the one that brought about the extinction of such spectacular animals as mammoths and mastodons, might have been a severe and sudden cooling of the planet. Louis Agassiz (Fig. 4) took this idea and developed it further, into the concept of a 'Great Ice Age.'

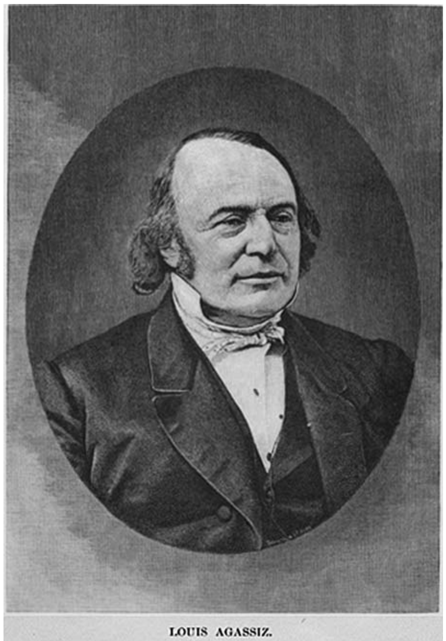

Figure 4 Louis Agassiz (1807–73).

Agassiz was a Swiss naturalist who started his career as Cuvier's assistant. Agassiz thought that mammoths and other extinct mammals must have been adapted to a tropical climate. Here is how he described their demise in the face of the oncoming ice age:

> The gigantic quadrupeds, the Mastodons, Elephants, Tigers, Lions, Hyenas, Bears, whose remains are found in Europe from its southern promontories to the northernmost limits of Siberia and Scandinavia···may indeed be said to have possessed the earth in those days. But their reign was over. A sudden intense winter, that was also to last for ages, fell upon our globe; it spread over the very countries where these tropical animals had their homes, and so suddenly did it come upon them that they were embalmed beneath masses of snow and ice, without time even for the decay which follows death.
>
> (Agassiz (1866), p. 208).

The Discovery of Pleistocene Glaciations

Agassiz's theory of the Great Ice Age was first presented to the Swiss Society of Natural Sciences in Neuchâtel in 1837. This was an ideal setting in which to convince geologists and natural historians, Agassiz could demonstrate the effects of glacial ice in the landscapes of the Alps (*see* Vertebrate Overview). He pointed to large boulders that had been transported by ice (glacial erratics), piles of rocks moved by glacial ice (glacial moraines), and scratched surface lines in bedrock, made by the passage of glacial ice and debris. Agassiz published his theory in the books *Étude sur les glaciers*, in 1840, and *Système glaciare*, in 1847. These books summarized his findings from Europe. He later found even more evidence of glaciation in North America. Agassiz's theory was initially rejected by many leading geologists, who still held to the idea that the transportation of surficial sediments was mainly due to the effects of the Biblical Flood. Agassiz's ideas on the glaciation eventually won the day, but his ideas about the nature of the Pleistocene megafauna turned out to be largely nonsensical. Far from being tropically adapted animals, the mammoths, mastodons, and other Ice Age mammals of Europe were adapted to the very same glacial environments to which Agassiz had ascribed their demise. Most of these animals died out during the transition to *warm* climate at the *end* of the last glaciation, not at its beginning.

Evidence for glaciation had been seen by some of Agassiz's contemporaries in other parts of Europe. For instance, Esmark noted the existence of glacial deposits in Norway, Bernhardi found evidence for glaciation in Germany, and de Venetz and Charpentier found evidence for the advance of glacial ice far beyond the limits of modern Alpine glaciers in Switzerland (*see* Vertebrate Overview). Agassiz himself traveled to Britain and North America and argued that surficial deposits that had previously been considered flood deposits should be reclassified as glacial.

Convinced by Agassiz's ice age theory, field geologists of the middle and late nineteenth century began looking for evidence to help reconstruct the actual history of glacial events. Agassiz had proposed a single, massive glacial event in which ice sheets covered much of the middle latitudes, as well as the high latitudes of the Earth. Evidence started accumulating that pointed to multiple glaciations, separated by warm periods. By the 1850s, evidence was pointing toward at least two major glaciations in Europe. By 1877, James Geikie (Fig. 5) had developed the concept of four or five large glaciations during the Pleistocene, based on stratigraphic evidence.

Evidence from North America made it clear that the last glaciation had not been the largest one, because it had not entirely destroyed the evidence for earlier, larger glaciations (*see* Late Quaternary in North America). Geologists coined the terms 'Nebraskan,' 'Kansan,' 'Illinoian,' and 'Wisconsinan,' to describe a sequence of four glacial epochs in North America. These were separated by three warm, or interglacial periods (the Aftonian, Yarmouthian, and Sangamon), based on the presence of ancient soils buried between glacial deposits.

Pioneering work on establishing the European glacial sequence was carried out by Albrecht Penck and Eduard Brückner (Fig. 6), who identified four glaciations, the Günz, Mindel, Riss, and Würm (*see* Late Pleistocene Glaciations in Europe).

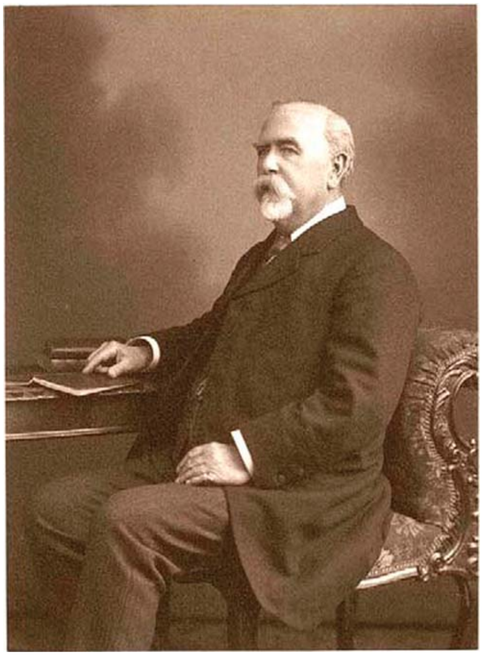

Figure 5 James Geikie (1839–1915).

Figure 6 Eduard Brückner (1862–1927) and Albrecht Penck (1858–1945).

These glaciations were named after four rivers in southern Germany. Penck and Brückner's (1909) work was based on the identification of the stratigraphic sequence of river terraces in the valleys of the northern Alps (**Fig. 7**). In many parts of the world, diligent field studies in the last century have failed to find evidence for more than four glaciations on land.

The ways in which these glaciations were recognized varied from one part of the world to another. In Europe, only the ice advances that reached farther south than younger ones were recognized as separate glaciations. The traces of any intermediate ice expansion were essentially overridden and destroyed by subsequent larger glacial advances. American glaciations were originally defined as times when the ice sheets extended south to the American Midwest. Interglacials were the times when the Midwest region was ice free. The classical North American Pleistocene subdivision is one of long interglacials and short glacials, whereas the North European system recognizes short interglacials and long glacials (Kukla, 2005). Penck and Brückner's Alpine glaciation scheme was the most widely used system of classification in the twentieth century for the correlation of Pleistocene deposits between continents (Flint, 1971) (*see* Overview).

Development of Theories on the Causes of Glaciation

As we have seen, by the late nineteenth century, the geologic evidence for repeated, large-scale glaciations of the globe was firmly established. The causes of glaciation, however, remained a mystery. Geikie's geologic evidence from Scotland showed that warm intervals had developed between glaciations. While the relative length of glacial and interglacial periods remained unknown, it was becoming clear that large-scale climatic oscillations had taken place over many thousands of years of Earth's recent history. Various suggestions were put forward to explain these cycles. Changes in carbon dioxide levels were proposed, as well as changes in solar intensity.

Croll's Orbital Theory

One of the earliest theories on the cause of glacial/interglacial cycles was developed by the Scottish scientist, James Croll (**Fig. 8**). Croll had little formal education, but he was a voracious reader.

In 1859, his pursuit of knowledge led him to enter academia 'through the back door,' by becoming a janitor at the museum at Anderson's Institution in Glasgow. Once there, he began developing a theory about the causes of glaciation. He began writing letters to Charles Lyell, discussing his ideas on the connections between glaciation and variations in the Earth's orbit. Lyell was suitably impressed with Croll's scholarship, and helped him obtain a clerical position at the Geological Survey of Scotland in 1867.

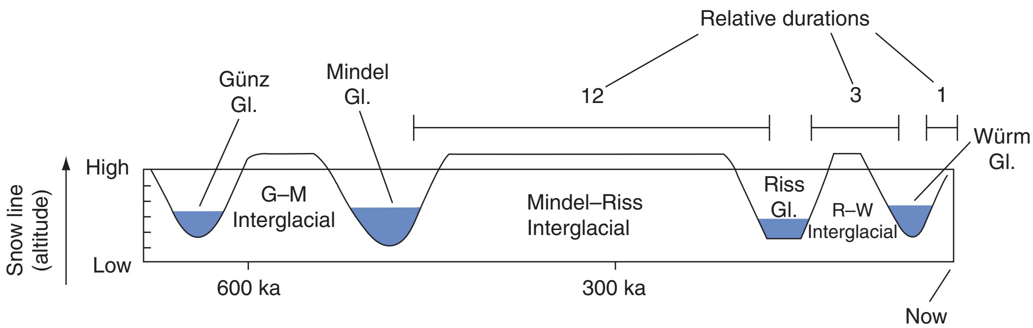

Figure 7 Diagram of European ice ages, their relative durations and the relative snow line during each. Note: During glacial periods snow fell at lower altitudes than during interglacial periods. Gl – Glacial; Intergl. – Interglacial. From Penck A and Brückner E (1909) *Die Alpen im Eiszeitalter*. Leipzig: Tachnitz.

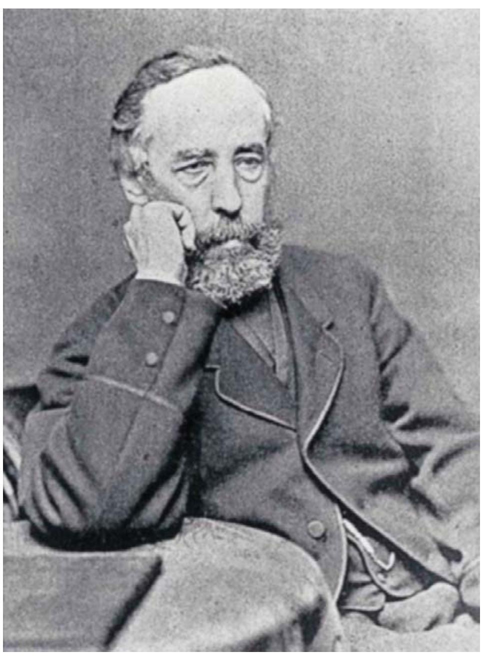

Figure 8 James Croll (1821–90). Photo by J. C. Irons, 1896.

It was here that Croll was encouraged by Archibald Geikie to further develop his theory. Charles Darwin was also a regular correspondent with Croll, and both scientists benefited from this exchange of ideas.

Croll started publishing his theories in 1867, and his major contributions include *Climate and Time, in their Geological Relations* (1875) and *Climate and Cosmology* (1885).

In 1846, French astronomer Urbain Le Verrier published formulas that allow the calculation of changes in the shape of a planet's orbit and its axial precession. In 1864, Croll used these formulas to plot changes in the shape of Earth's orbit (called orbital eccentricity) over the past 3 Myr. He found that a pattern of high eccentricity had persisted for hundreds of thousands of years, followed by a pattern of low eccentricity, as is the case today. The more elliptical the orbit, the greater the difference in incoming solar radiation (insolation) between the different seasons of the year. Croll realized the importance of calculating the seasonality of insolation, which is one of his major contributions to the science of paleoclimatology. Changes in Earth's orbit that act to prolong the winter season cause greater amounts of snow to accumulate in the high latitudes (Fig. 9).

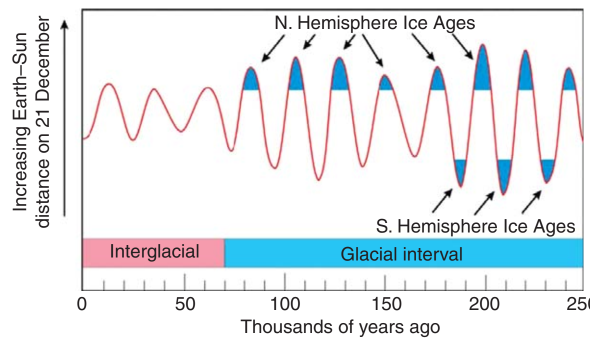

Figure 9 Diagram illustrating Croll's (1887) explanation of ice ages, based on changes in Earth's orbit around the Sun.

The extra snow cover reflects more solar energy back out into space, thereby amplifying the orbital effects. Croll argued that this amplification is what triggers the growth of ice sheets.

Croll's theory introduced important new concepts in the field of climatology. Subsequent research has shown that Croll's theory is insufficient to explain the global pattern of Pleistocene glaciations, and Croll's chronology of glaciations has been shown to be in error. Specifically, Croll's scheme made the last ice age much older than was inferred from the geologic evidence of Geikie and others. Ultimately, Croll failed to convince most of his contemporaries, and his ideas remained largely ignored by other researchers until the 1940s.

The Milankovitch Theory

Milutin Milankovitch (Fig. 10) was a Serbian mathematician who specialized in astronomy and geophysics.

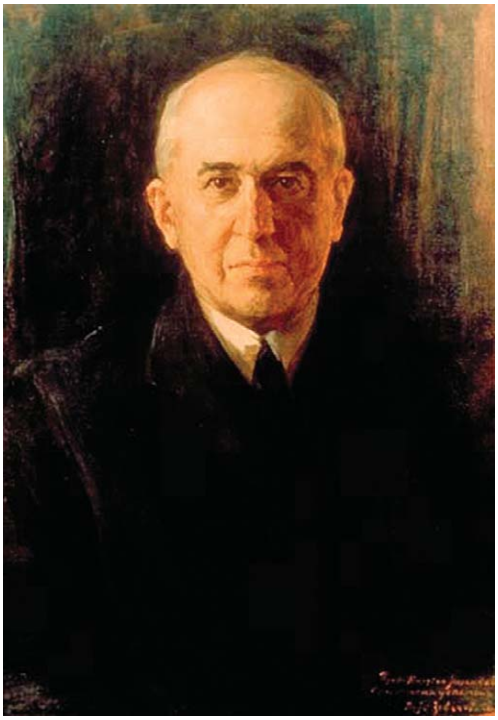

Figure 10 Portrait of Milutin Milankovitch (1879–1958) by Paja Jovanovic, 1943. Courtesy of the Serbian Academy of Sciences and Arts.

In 1909 he became a member of the faculty in applied mathematics at the University of Belgrade.

Imprisoned by the Austro-Hungarian Army in the First World War, he recommenced work on his mathematical theory of climate change in 1920, completing this work in 1941. Milankovitch built his theory from previous work done by J.A. Adhemar and James Croll. In 1842 Adhemar explained glacial climate using only precession. Milankovitch used Croll's work to help him develop a mathematical model of climate change. This model incorporates the cyclical variations in three elements of Earth's orbit around the Sun: eccentricity, obliquity, and precession. Using these three orbital factors, Milankovitch developed a comprehensive mathematical model that calculated latitudinal differences in insolation and the corresponding surface temperatures during the last 600 kyr (*see* Milankovitch Theory and Paleoclimate, and Introduction) (Fig. 11).

The next step in Milankovitch's work was an attempt to correlate the orbital variations with glacial/interglacial cycles. Milankovitch worked on the assumption that radiation changes in some latitudes and seasons are key to triggering glaciation and deglaciation. Working with German Climatologist Vladimir Koppen, he chose the summer insolation values at 65° N as the critical latitude and season. Their reasoning was that the continental ice sheets grew near this latitude, and that cooler summers might reduce

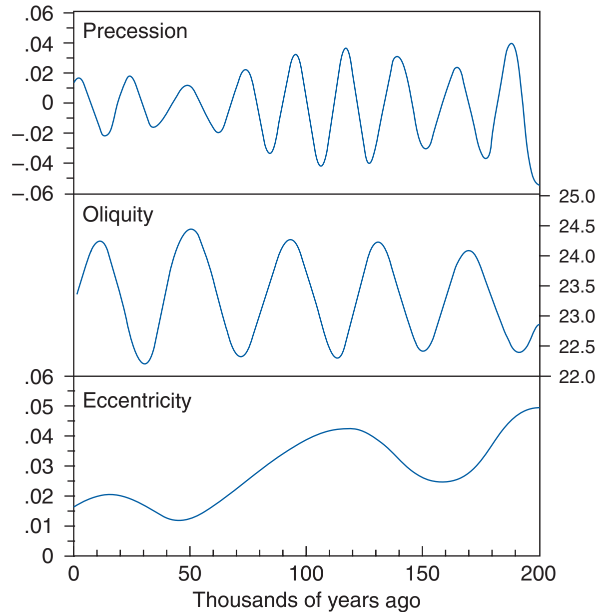

Figure 11 Orbital variations predicted by the Milankovitch theory. From Berger A and Loutre M F (1991) Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews* 10: 297–317.

summer snowmelt, leading to a buildup of snow pack, and eventually to the growth of ice sheets.

Sadly, Milankovitch's theory was largely ignored for decades. However, in 1976, Hays *et al.* published a study of deep-sea sediment cores and found that Milankovitch's predictions matched their own interpretations of the timing and intensity of climate change during the last 450 kyr (*see* Paleoceanography). Specifically, they found that major variations in climate were closely associated with changes in the eccentricity, obliquity, and precession of Earth's orbit.

The Invention of Dating Methods

Without a means of obtaining an absolute age for events in the Quaternary, there would have been no way to test the validity of Milankovitch's orbital variation theory. Until the latter half of the twentieth century, Quaternary scientists lacked the tools to obtain such absolute ages, and could only infer the ages of events through relatively dating techniques. In other words, they could sometimes establish the 'sequence' of events, for instance, by determining the relative stratigraphic position of various kinds of fossils. But they could not tell whether a given sequence of events took place 50 or 150 ka, unless they were dealing with long sequences of sedimentary layers that accumulated in recognizable, annual layers (a very rare phenomenon).

Uranium-Series Dating

Radiometric dating methods were developed in the twentieth century, and have revolutionized Quaternary science. In 1902, physicists Ernest Rutherford and Frederick Soddy had discovered that radioactive elements broke down into other elements in a definite sequence or series, through the process of nuclear fission. The possibility of using this radioactivity as a means of measuring geologic time was first discussed by Rutherford in 1904. In 1906, Rutherford began calculating the rate of radioactive decay of uranium. This decay process (uranium decaying to lead) has since been discovered to go through multiple steps, with intermediate daughter products. It is now possible to use various uranium-series decay processes to derive age estimates for uranium-bearing fossils and sediments, back many millions of years (*see* Paleoceanography).

Radiocarbon Dating

Perhaps the most important breakthrough in the absolute dating of Quaternary fossils and sediments was the invention of radiometric dating methods, especially radiocarbon dating. In 1940, American physicists Martin Kamen and Sam Ruben discovered the long-lived radioactive carbon isotope, carbon-14. Kamen used ^{14}C as a tracer in biological systems. Kamen found that some of the nitrogen in the atmosphere was turned into carbon-14 when bombarded with cosmic rays. The existence of ^{14}C had been postulated since 1934, but it had never been directly observed nor characterized. Kamen succeeded in preparing ^{14}C in sufficient amounts to determine its half-life (5700 yr), that is, the amount of time it takes for half of a sample of ^{14}C to break down to the stable ^{14}N isotope of nitrogen (*see* Conventional Method).

Building on Kamen's discoveries, in 1947 American chemist Willard Libby (Fig. 12) determined that plants absorb traces of ^{14}C during their uptake of carbon in photosynthesis. At death, the plant would stop absorbing carbon, and the ^{14}C it contained would decay at its usual rate without being replaced. By measuring the concentration of ^{14}C left in the remains of a plant, Libby (1952) discovered that it was possible to calculate the amount of time since the plant had died. In addition, it was found that the same concentrations of ^{14}C occur in the tissues of animals as in plants, since animals either directly or indirectly ingest the carbon from plant tissues as their food. Given that it is possible to measure the concentration of remaining ^{14}C back to nine or ten half-lives, it has thus become possible to obtain absolute age estimates of fossil specimens (both plant and animal), back to about 45–50 kyr. For his work on carbon-14 dating, Libby received the Nobel prize in chemistry in 1960.

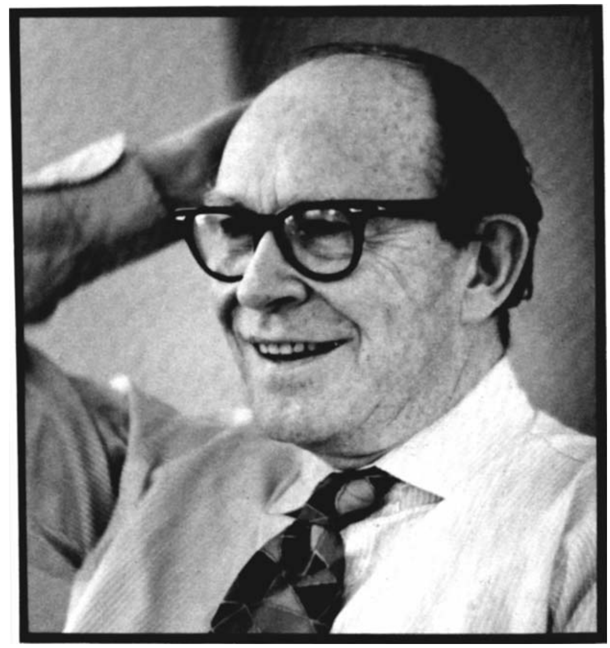

Figure 12 Photograph of Willard F. Libby, inventor of the radiocarbon dating method. Photo courtesy of Geoscience Analytical Inc.

Conclusions

Other articles in this Encyclopedia will highlight the state of the art in the above-mentioned fields of Quaternary stratigraphy, vertebrate paleontology, Pleistocene glaciology, paleoclimatology, and dating methods. As with all branches of science, the current generation of researchers has built on the foundations of people such as Agassiz, Lyell, Cuvier, Milankovitch, and Libby. We owe these pioneers an enormous debt of gratitude. Many of these people worked in relative obscurity during their own lifetimes, and their theories were openly ridiculed by their contemporaries. Many survived major political upheavals and wars in the rapidly changing world of the nineteenth and twentieth centuries. The unifying themes of their lives are their intellectual curiosity, their diligence and perseverance, and their breadth of vision. May the same be said of twenty-first century Quaternary scientists, by future generations.

See also: **Glaciation, Causes**: Milankovitch Theory and Paleoclimate. **Glaciations**: Overview; Late Pleistocene Glaciations in Europe; Late Quaternary in North America. **Introduction**: History of Recent Major Projects. **Paleoceanography**. **Paleoclimate**: Introduction. **Quaternary Stratigraphy**: Overview. **Radiocarbon Dating**: Conventional Method. **Vertebrate Overview**.

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History of Dating Methods

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The first methods for dating Quaternary materials resulted from the discovery of radioactivity 120 years ago. In addition, other dating methods have been developed that rely on other time-dependent changes that occur in natural materials. The different methods can be used to obtain the age of formation of either organic or inorganic materials.

Early Developments

Numerical dating methods based on natural radioactive phenomena were initially developed as a means of determining the age of the Earth (Dalrymple, 1991). Arguments on this topic raged in the second half of the 19th century, a time when the effects of recent glaciation were also being debated. However, it was not until the discovery of radioactivity in the 1880s that consideration was given to radioactive isotopes for use as natural clocks. As early as 1906, Rutherford suggested that ages could be obtained based on the production of helium by the decay of uranium in rocks. The first calculation of the age of the Earth based on the amount of radium in the Earth's crust was made by Russell in 1921. However, it was not until the 1930s, when Nier brought together the understanding of natural isotopes in the uranium and thorium decay chains and the construction of the first mass spectrometers, that it became possible to measure a range of isotopes. Also at this time, the potential of several different decay series that could be used for dating was proposed, based on a better understanding of the atomic structure of elements in the periodic table. The relationship between these early radiometric dates and the evolution of the geological timescale has been covered in a history of the work of Arthur Holmes (Lewis, 2000).

Radiocarbon Dating

The speed at which new geochronological tools based on radioactivity became relevant to Quaternary